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ART VII.—*The Geology of the Korkuperrimul Creek Area, Bacchus Marsh.*

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Introduction.

The area described in this paper lies approximately 1 mile west of the Township of Bacchus Marsh, which is 33 miles west-north-west of Melbourne.

There are two main occurrences of Permo-Carboniferous rocks along the Korkuperrimul Creek—

(*a*) The Bald Hill area (¾ square mile), which lies 1 mile west of Bacchus Marsh. Here Permian beds with *Gangamopteris* leaves are overlain without angular unconformity by the only definitely recorded Triassic rocks in Victoria.

(*b*) The North Korkuperrimul area (1¼ square miles), which is 2 miles north-north-west of the Bald Hill area. It has been comparatively neglected by geologists, the only references to it being those of

David (1896), and Sweet and Brittlebank (1893); yet it is unique in the Bacchus Marsh district in that it provides an almost complete section along the dip through some 2,000 feet of sediments.

Between the above two areas, the Korkuperrimul Creek flows in a steep-sided valley cut through the Older Volcanics. To the west, the Pentland Hills extend for several miles and, except for a few small outliers of Tertiary sands, consist entirely of basalt. To the east is Bald Hill, which is also composed of Older Volcanics. The total area of basalts dealt with is about 5 square miles, and is bounded in the north and north-east by the Greendale fault and in the east by the Rowsley fault, while to the south the Older Volcanics dip under Tertiary sands and to the west they are overlain by the Newer Basalt flow from Mt. Blackwood.

Previous Work.

Summers (1935) has given a summary of our present knowledge of the Permo-Carboniferous rocks and an extensive bibliography will be found in an earlier paper (Summers, 1923).

The first record of Older Volcanics in this district consists of a few brief notes in the Progress Reports of the Geological Survey for 1863 (reprinted in 1897). Fenner (1918) mentioned the Older Volcanics and the Permian rocks in connexion with the physiography and faulting of this area, but he did no detailed work on them.

The map is taken, with few alterations, from portions of quarter-sheets 11 S.E. (unpublished) and 12 N.E. (published 1868), the boundary between these two running east-west across Anderson's Quarry. Both were mapped on the scale of 2 inches to 1 mile. Later maps issued by the Geological Survey are the geological sketch maps of the Werribee Gorge and adjacent country (1914) and of the Bacchus Marsh district (1925), both of which are on a scale of 1 inch to 1 mile. The contours are taken from the Military Survey map of Ballan.

Faulting.

The whole area is complexly faulted, minor faults being common. The more important faults are described below.

The Rowsley fault was shown by Fenner (1918) to mark the eastern boundary of the Bald Hill area of Permian and Triassic rocks. The somewhat irregular boundary here between Triassic and Tertiary beds indicates that the fault passes into a monocline in this part of its course.

The Greendale fault forms the northern and eastern boundaries of the North Korkuperrimul area of Permian rocks. East of

Long Gully, it cannot be observed in section, but the nature of the mapped junction between Permian and Ordovician suggests that the fault does extend down Long Gully (see map).

The Bald Hill faults (F.1 and F.6, see map) were noted by Fenner (1918). F.1 marks the junction between Permian to the south and Older Volcanics to the north, but is not visible in section. From a study of the lava sequence, it has been proved that this fault continues across the creek into the Older Volcanics of the Pentland Hills. F.6 marks the western boundary of the Bald Hill area and may be seen in several sections along the Korkuperrimul Creek (Plate VII., fig. 2). Each of these faults must have a throw of several hundred feet.

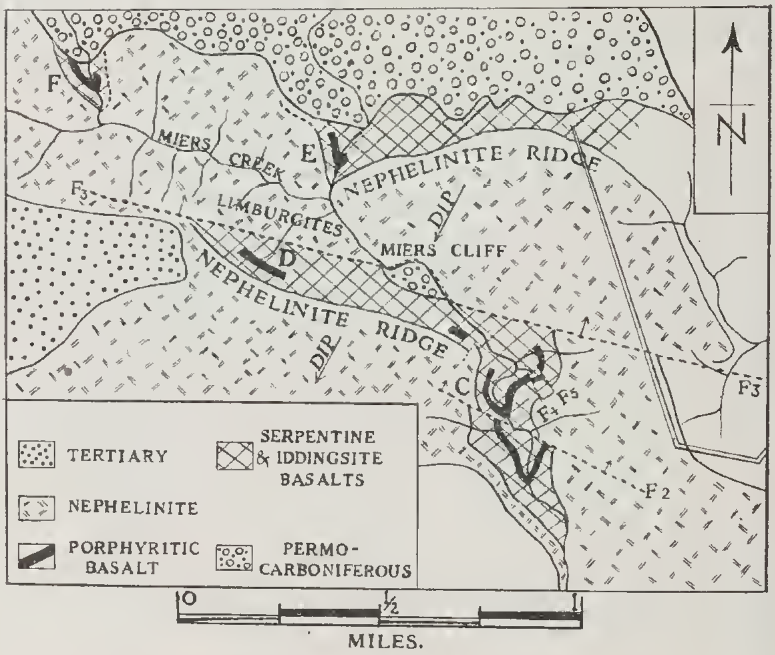

Fig. 1.—A geological sketch map illustrating the relationships of the Pentland Hills fault (F$_3$ on the figure).

The Pentland Hills fault (Fig. 1), with a downthrow of 500 to 1,000 feet to the north, passes immediately to the north of Mier's Cliff. Its presence is indicated by two lines of evidence—

(*a*) The sequence of Permian beds in Mier's Cliff is the same as that seen at Anderson's Quarry, which is over half a mile upstream, though at much the same height above sea level. No important change in the amount or direction of dip can be observed between these two localities. Such a feature can best be explained by postulating an east-west fault, with the downthrow to the north, lying somewhere between the southern boundary of the North Korkuperrimul area and Mier's Cliff. Assuming the dip of the Permian to be 25 deg. to 30 deg. to the south-south-west, the throw of this fault cannot be much less than 1,000 feet.

(*b*) The proposed sequence of the Older Volcanics (q.v.) affords evidence which allows us to fix the position of this fault more closely. Immediately to the north of the cliff, olivine nephelinite rests against Permian at creek level, while to the south the same olivine nephelinite occurs several hundred feet above creek level, dipping gently to the south. Such a displacement must be due to a fault running east-west immediately north of Mier's Cliff. The section (Fig. 7) indicates that the throw of this fault probably exceeds 500 feet. The fault has been traced for well over a mile. The irregularity in the fault-line at Mier's Cliff may be due to a number of subsidiary faults, intersecting the main fault obliquely.

Of the other faults which have been recognized, F.2 (Fig. 1) has a downthrow of 80 to 100 feet to the north-east. It may be seen in section on the west bank of the creek, where it is almost vertical and is characterized by a fault zone 3 to 4 feet wide, impregnated with carbonates. F.3 and F.4 are two smaller faults seen on the east bank of the creek, about 200 yards east of Section C (see Fig. 6).

Generally the basalts have a much lower dip than the Permian beds though they dip in the same general direction. Moreover, the calculated displacement of the Older Volcanics along the Pentland Hills fault is much less than that of the Permian beds along the same fault-line. These facts indicate that the Permian suffered a certain amount of tilting and displacement before the basalts were extruded and that later tilting of both Permian and basalts occurred in post-Older Volcanic times.

The Permian Rocks.

By T. R. SCOTT, M.Sc.

(A) General Geology.

Dip of the Permian Beds.

In the North Korkuperrimul area the average dip of the beds is at least 35 deg. and varies from 64 deg. to 27 deg. The direction of dip varies between S. 14°W. and S. 30°W., the average being S. 24°W. (mag.). The variation in the amount of dip may be due either to local faulting and warping or to variation in the thickness of individual beds. The very high dips (50 deg. to 64 deg.) seen in the Korkuperrimul Creek at the southern boundary of the Permian are probably due to faulting along the line of the Pentland Hills fault in pre-Older Volcanic times. Very low dips occur only in the north-west corner of the area.

At Mier's Cliff, the average dip is 36 deg. to the south-south-west, though local open folds occur at right angles to the regional tilt.

In the Bald Hill area, the direction of dip is easterly, varying from E. 12°S. to almost due north, while the amount of dip varies between 40 deg. and 23 deg., with an average of 30 deg. The Triassic beds show no angular unconformity with the Permian beds below them. Along the Bald Hill ridge; from the Council Trench northwards, the direction of dip is consistently a few degrees south of east, but in the deep gulch in the north-east corner of the area, it is E. 38°N. From this point to the Main Quarry, the strike continues to change, until at the Main Quarry itself the direction of dip is E. 66°N. In the western part of this area, the dip is low. At Bald Hill, there appears to be a close relation between the dip of the Permian and Triassic beds and the bounding faults. If the Rowsley displacement, which forms the eastern boundary here, is monoclinal in this part of its course, as Fenner (1918) suggested, the beds should dip towards its downthrow side; this actually does occur. Along the northern boundary of the Bald Hill area, the beds strike almost parallel with the east-west fault (F.1) and dip towards its downthrow side. This result is probably due to the downward drag which is frequently seen in the beds on the upthrow side of a fault. In the north-east corner of the Bald Hill area, where the two fault lines should intersect, the attitude of the beds is a compromise, the dip being to the north-east.

Apart from the Bald Hill area, however, the Permian of the whole Korkuperrimul Creek area shows a well-marked regional dip to the south-south-west, which is also seen (Sweet and Brittlebank, 1893) in the glacial beds of the Werribee Gorge and Lerderderg Gorge areas.

Sequence and Thickness of the Permian in the North Korkuperrimul Area.

It is only in the North Korkuperrimul area that a good sequence of the Permian can be obtained, as was realized by David (1896). The present author's interpretation of this sequence is given in the accompanying table (Table 1).

This interpretation of the sequence differs from that of David (1896, 1920) in the following points:—

1. David based his estimate of the thickness on an average dip of 30 deg., whereas it is now believed that the average is not less than 35 deg.

TABLE No. 1.

Sequence of the Permian from Anderson's Quarry to Cockatoo Gully, in the North Korkuperrimul Area.

Stage No.	Description.	Thickness in Feet.	
		Formations.	Stages.
1	Glacial conglomerate (" winnowed tillite ")	..	25
2	Sandstones containing fossil wood, with intercalated clay bands near the base	..	200
3	Glacial mudstones, brown above, blue-grey below, jointed and poorly bedded, with occasional bands of grit or sandstone	..	347
4	Tillites, sandstones and mudstones. Starting from the top beds, the formations are :—		
	(*a*) Sandstones	69	
	(*b*) Conglomerate	1	
	(*c*) Tillite, perhaps in part glacial mudstone	83	
	(*d*) Sandstones	35	
	(*e*) Tillite	18	
	(*f*) Mudstones and sandstones	7	
	(*g*) Glacial mudstones	9	
	(*h*) Well-bedded sandstones and pebbly mudstones, multi-coloured	17	
	(*i*) Jointed glacial mudstones	18	
	(*j*) Sandstones and brown jointed shales	23	
	(*k*) Jointed glacial mudstones	12	
			292
5	Well stratified sandstones	..	71
6	Tillite, sandstones and conglomerates. Formations are as follows :—		
	(*a*) Tillite with thin bands of sandstone and pebbles	11	
	(*b*) Sandstones	13	
	(*c*) Jointed tillite	7	
	(*d*) Shales and sandstone with conglomerate at the base	29	
			60
7	Tillite, passing down into glacial mudstones	..	153
8	Conglomerate and sandstones	..	150
9	Tillite, with bands of sandstone and conglomerate; passes down into glacial mudstones	..	220
10	Tillite Creek Stage. Formations are :—		
	(*a*) Sandstones	45	
	(*b*) Tillite	35	
	(*c*) Laminated shales (impersistent)	4	
	(*d*) Sandstones and conglomerate	56	
	(*e*) Tillite with intercalated sandstones	30	
	(*f*) Laminated shales (impersistent)	6	
	(*g*) Sandstones and conglomerate	20	
	(*h*) Tillite (at mouth of Tillite Creek)	45	
	(*i*) Sandstones and conglomerates	24	
	(*j*) Tillite	4	
	(*k*) Sandstones and conglomerate	29	
	(*l*) Tillite with intercalated sandstones and gravel	67	
	(*m*) Hard laminated sandstones	4	
	(*n*) Sandstones with basal conglomerate	14	
	(*o*) Tillite	42	
			425
11	Sandstones and conglomerates at mouth of Cockatoo Gully	..	60
12	Glacial mudstones (englacial deposits ?) with thin bands of calcareous sandstone	..	100
	Total thickness	..	2,103

2. David gave a thickness of only 30 feet to the beds of Stage 2, though in the North Korkuperrimul area they are quite 200 feet thick.

3. In Stage 10, David stated that repetition of strata was caused by a large fault of 120 feet throw. The author has been unable to find any sign of such a fault.

4. The author agrees with David (1920) that the boulder beds of Stages 7 and 9 (upper parts) and 10 are true tillites. But the beds of Stage 12, which David called tillites, apparently believing them to be equivalent to the basal tillites of Werribee Gorge and Coimadai Creek, are distinctly stratified and therefore cannot be true tillites. It is also believed that several tillites occur in Stage 4, though none are mentioned here by David.

The Base of the Series.

David implied that the glacial mudstones of Stage 12 were the basal beds of the Permo-Carboniferous, resting unconformably on the Ordovician, but actually these beds are faulted against the Ordovician in Cockatoo Gully (along the line of the Greendale fault). Thus there are probably beds below Stage 12 which are not exposed. The basal beds of the Permo-Carboniferous differ so greatly from place to place (e.g. Coimadai Creek, Werribee Gorge, Myrniong Creek) that the exact stratigraphical position of Stage 12 with respect to the base of the glacial series cannot be determined. All that can be done is to allot to Stage 12 a minimum thickness of 100 feet, in which case our estimate of the thickness of the whole series is the minimum value, viz., 2,103 feet.

The Top of the Series.

In the North Korkuperrimul area, the beds of Stages 1 to 3 are seen along the creek from the junction with Long Gully down to the southern boundary of the area, and also in Anderson's Quarry. At the latter locality, Stage 1 is overlain by well stratified red, yellow, brown and purple sandstones and mudstones, generally very hard, and quite different from any of the sandstones lower down in the series, being often micaceous and considerably indurated. At Mier's Cliff, this same sequence, from the hard sandstones above Stage 1 down to the glacial mudstones of Stage 3, is seen again, the lithological resemblance to the Anderson's Quarry section being so close as to warrant immediate correlation of the beds at the two localities.

Moreover, this same sequence is again found at Morton's Quarry in the Bald Hill area, where the mudstones of Stage 3 are only seen in a miniature canyon several hundred yards north of the quarry. These glacial mudstones are overlain by the *Gangamopteris* sandstones of Morton's Quarry, above which is a thin conglomerate, which in its turn is overlain by hard multi-coloured sandstones and mudstones. It is probable that the *Gangamopteris* sandstones of the Main Quarry belong to the same horizon as the similar beds at Morton's Quarry.

It is therefore held that the sandstones of Morton's Quarry, Mier's Cliff and Anderson's Quarry all belong to the same horizon.

The conglomerate which overlies these sandstones at all the above localities has characteristic features. It contains numerous pebbles and boulders which are rarely striated and often sub-angular and even rounded. Many of the pebbles are foreign to the district, decomposed granites being very common. The matrix of the rock varies in grain size from coarse to very fine. It is often rudely stratified and sometimes contains fossil wood. At Bald Hill, this conglomerate makes a sharp junction with the underlying sandstones, which at Morton's Quarry show strong contortion and other features, probably due to the movement above them of an ice sheet or glacier (q.v.). The striking feature about this conglomerate is that, although very hard, it seems to have been deeply weathered at some time. As the above evidence shows, it is not a true tillite. David called it a "winnowed" (redistributed) tillite and such a description agrees with its properties very well, for it does not resemble any of the glacial mudstones in the area.

This winnowed tillite therefore marks an erosion interval and in fact was considered by David to mark the interval between the so-called Permo-Carboniferous beds and the Triassic beds at Bald Hill.

The Age of the Series.

The hard mudstones and sandstones above the winnowed tillite at Morton's Quarry were believed by David to be Triassic in age, and the similar beds at Mier's Cliff and Anderson's Quarry must be of the same age. Since at each of these three localities the lowest Triassic beds rest on the same horizon of the Permo-Carboniferous, viz., the winnowed tillite, the erosion interval between the Triassic and the Permo-Carboniferous must have been extremely short. Otherwise, differential erosion would have caused the lowermost Triassic beds to rest on different Permo-Carboniferous horizons at different localities.

Now there are 400 feet of sediments between Morton's Quarry and the Council Trench, where a Triassic flora is found (Chapman, 1927). If the top of the winnowed tillite marks the Permian-Trias interval, then this 400 feet of sediments must have been accumulating through a great part of Triassic time. The lithological nature of these beds indicates that this is quite likely. But since the Permian-Trias interval was so short, the *Gangamopteris* sandstones must represent the uppermost Permian; yet David (1920) correlated tentatively the whole of the Bacchus Marsh beds with the Upper Carboniferous Lochinvar glacial beds of New South Wales. However, the resemblance between the Lochinvar beds and those at Bacchus Marsh is only superficial. While the beds at Lochinvar contain marine fossils, there is no evidence to indicate that the Bacchus Marsh beds were formed under marine conditions. Further, while glacial pavements and true tillites are developed at Bacchus Marsh, neither has been observed at Lochinvar. (The only formation which physically resembles the Bacchus Marsh deposits to any degree of closeness is the glacial stage of the Kuttung (Upper Culm) series of New South Wales, which shows a considerable development of tillites and fluvio-glacial deposits, and is largely the product of a land-ice glaciation.)

The lithological nature (q.v.) of the beds of the Korkuperrimul Creek area indicates that they must have accumulated fairly rapidly. This suggests that the 2,000 feet of sediments at Bacchus Marsh accumulated during only a portion of Permo-Carboniferous time, particularly as several thousand feet of similar sediments accumulated during the Kuttung (Upper Culm) period in New South Wales.

Therefore, since the *Gangamopteris* sandstones and the winnowed tillite are uppermost Permian in age (*vide supra*), it is believed that the whole of the Bacchus Marsh beds, with the possible exception of the basal tillites resting on the Ordovician, are Upper Permian in age. They will be referred to as such in the sequel.

B. PETROLOGY.

Erratics.

The term "erratic" is used here to denote the boulders and pebbles found in sediments of glacial origin. A large number of erratics from the Bald Hill and North Korkuperrimul areas have been studied by the author in the hope that some might be traceable to their source rocks. Most of the erratics are sedimentary types closely resembling the Ordovician rocks of the Bacchus Marsh area, and a search for unusual types resulted as follows:—

Igneous Rocks.

	Number of Specimens.
Granites—dominantly alkaline, with little biotite but common muscovite, occasionally garnetiferous	34
Pegmatites, aplites, &c.	8
Greisen, with much tourmaline and rare topaz	3
Quartz and felspar porphyries	8
Rhyolites, including resilicified aegirine rhyolite	2
Reef quartz	2

Metamorphic Rocks.

	Number of Specimens.
Granitoid rock with abundant andalusite, garnet and tourmaline	1
Gneiss and schist (biotite and muscovite types) ..	14
Cordierite hornfels	3
Slate and phyllite	10
Jasper	1
Cream-coloured rock with numerous brown spots (hornfels?)	3
	89

Sedimentary Rocks.

Sandstones and quartzites are very common, with occasional grits and mudstones. Limestones are absent.

Unfortunately, distinctive as many of these specimens are, they cannot be satisfactorily traced to their source rocks, since they either occur *in situ* at a number of widely-separated localities or cannot be matched with any known Victorian rocks. Assuming that the ice sheets came from the south-west (Summers, 1935), the above difficulty arises from the fact that all the pre-Permian rocks of the country south-west of Bacchus Marsh are entirely covered by Jurassic sediments or Tertiary basalts. All that can be done at present is to place on record the great variety of erratics in the Bacchus Marsh Permian beds.

Heavy Mineral Assemblages.

The heavy mineral assemblage of the Permian sediments at Bacchus Marsh is quite characteristic, though the proportions of the various minerals vary widely. The heavy mineral index varies between .05 per cent. and .3 per cent. The mineral species present are zircon, apatite, tourmaline, and garnet, which constitute 90 per cent. of the assemblages, together with smaller amounts of rutile, leucoxene, muscovite, biotite, iron oxides and ilmenite. Rarer minerals are staurolite, kyanite, sillimanite, brookite, dumortierite, corundum, various metallic sulphides, and possibly gold and anatase. The heavy mineral assemblage of the Triassic is very similar to that of the Permian, though kyanite is more common in the Triassic.

The heavy mineral assemblage of the Permian sediments is characterized by the abundance of highly stable minerals, such as garnet, zircon, tourmaline and rutile. The heavy minerals of the sedimentary erratics, and of the Ordovician *in situ* in the Bacchus Marsh area, show a distinct resemblance to the Permian heavy minerals, containing abundant apatite, tourmaline, zircon and rutile. It appears, therefore, that the Permian rocks were largely derived from the Ordovician sediments surrounding

Bacchus Marsh. Support is given to this belief by the fact that the brown apatite and pleochroic blue tourmaline which occur in small amounts in the Permian are also found in the Ordovician. One difficulty appears, however, for in the Ordovician heavy minerals which have been studied, pink garnet is absent and only 1 per cent. of colourless garnet can be found, though both are common in the Permian. The source of this garnet has not been discovered as yet, though certain granitic erratics in the Permian tillites do contain pink garnets in small amount.

The Occurrence of Apatite.

Boswell (1933) claims that "the presence or absence of apatite is determined to a very great extent by the local conditions as regards the permeability of the containing rocks to (carbonated) water." If these views are applicable to the Bacchus Marsh beds, the sandstones (porous) and the tillites (relatively impermeable) should differ appreciably in the proportion of apatite which they contain. This does not occur, however, nor does the degree of corrosion (due to solution) of the apatite vary with the permeability of the containing rocks. Moreover, the bands of calcareous sandstone in Stage 12 of the North Korkuperrimul area contain abundant apatite, yet these sandstones have obviously been traversed by carbonated waters.

In the Bacchus Marsh Permian beds, therefore, the apatite appears to have survived at least one cycle of erosion (two cycles, where it has been derived from the Ordovician sediments), and has only succumbed to a small extent, if at all, to the attack of carbonated waters. These facts suggest that apatite may sometimes be much more stable to erosion and solution than is generally believed.

Nature and Origin of the Sediments.

The sandstones are coarse and medium-grained, generally well stratified and with argillacious, limonitic or calcitic cement. The latter type is fairly common, sometimes containing up to 50 per cent. of calcite, as in Stage 12.

The conglomerates are hard and rudely stratified, the pebbles being generally sub-angular. They may grade vertically and laterally into gravel and thence into sandstone.

Where sandstone and conglomerates are intimately associated, as frequently happens in the Bacchus Marsh Permian beds (see Plate VII., fig. 4), they are believed to be fluviatile (fluvioglacial) in origin. That this is true for the conglomerates is shown by their rude bedding and impersistent nature, together with the roundness or sub-angularity and the incomplete sorting of the contained pebbles. A similar origin for the sandstones is indicated by the strong current bedding of the sandstones (except for the laminated types), their lenticular nature in many cases and the considerable amount of lateral variation in lithology, and the linguoid ripple-marks in the sandstones of Stage 8, which, according to Bucher (1919), generally indicate a fluviatile environment. The well stratified and laminated sandstones, such as the *Gangamopteris* sandstones, were probably formed in shallow lakes.

Shales (grain size 0.03 mm.) are fairly common, especially in Stage 10, where they are always found immediately below a tillite horizon. They are usually laminated, but no seasonal banding has been observed. Erratics are rare in these rocks and do not indent the strata appreciably. Probably the shales are partly lacustrine and partly fluviatile in origin, since they may either grade up into lacustrine glacial mudstones (q.v.) or pass down into fluviatile sandstones.

In the Bacchus Marsh area, there are two types of boulder beds, generally intimately associated. These are glacial mudstones (lacustrine) and tillites (which were the ground moraines of glaciers or ice-sheets). At times, the change from tillite to glacial mudstone is gradual and no sharp line of division can be drawn between the two types. The lowest section of Permo-Carboniferous in Coimadai Creek is undoubtedly tillite, the contact with the Ordovician clearly showing the plucking and gouging action of the ice-sheet. Along the Korkuperrimul Creek, however, apparently unstratified boulder beds often pass without a break into well bedded mudstones. Such boulder beds, though physically resembling the tillites, could not have been the ground moraines of ice-sheets.

Microscopically, there is little difference in grain size and shape between the glacial mudstones and tillites. The tillites are frequently sandy in texture, due to the incorporation of previously formed sands (q.v.) and they also contain at times irregular bands and lenses of sandstone, as well as pockets and strings of conglomerate and gravel. The glacial mudstones, however, are consistently fine-grained and only rarely contain bands of grit or ferruginous sandstone, which are quite different from those seen in the tillites.

The erratics in the glacial mudstones are perhaps smaller, less numerous and less frequently striated, than those occurring in the tillites. The essential constituent mineral is quartz. Felspars are rare and always weathered. The tillites are invariably hard, but the glacial mudstones are sometimes much softer.

The tillites are generally brown in colour, but the glacial mudstones show considerable variety, most frequently being light brown or grey-blue.

Though the tillites are invariably unstratified, the glacial mudstones occasionally show bedding. The presence of pockets and lenses of sandstone and gravel in tillite does not necessarily mean that the tillites are stratified. The extensive jointing of the boulder beds sometimes gives the impression of stratification, especially when certain of the joint planes dip in the same direction as the stratified beds of the area (see Plate VII., fig. 3). At times, these joints may curve round, or stop at the junction with, large erratics. This has led to the erroneous belief that the bedding planes of the rocks have been indented by the larger erratics. Actually, such a phenomenon can only occur in the rare cases where large erratics are found in bedded rocks and it is not general even under these circumstances.

Tillites (Plate VII., fig. 3).

That the tillites were once the ground moraines of glaciers or ice-sheets is clearly shown by their peculiar lithological nature, the absence of stratification and the striated pebbles which they generally contain. The presence of bands and pockets of sandstone, gravel and conglomerate in the Bacchus Marsh tillites (Plate VII., fig. 1) may have been one of the factors which led the early investigators to doubt their ground-morainic nature. However, J. Geikie (1894) points out that "nests and irregular patches and lenticular layers and thick beds of water-arranged material are not infrequently enclosed in till": while Salisbury (1896) states that an advancing glacier may often incorporate the previously-formed deposits of its extra-glacial streams and lakes, and shows how sub-glacial streams may sometimes be responsible for the formation of quite large amounts of sand and gravel, &c., in the actual body of the ground moraine.

If the tillites of the North Korkuperrimul area were ground moraines of ice-sheets, the sediments above which the ice moved should show some evidence of such movement above them. Such evidence is present, but only to a limited extent, mainly because the Permian beds were probably more or less horizontal until at least Triassic times and thus offered little resistance to the passage of ice-sheets over them. The sandy nature of certain tillites and the presence in them of erratics of Permian sandstones (sometimes very large, as in Stage 9) indicate the influence of glacial action on the Permian sediments. The shales beneath the two top tillites in Stage 10 in the North Korkuperrimul area show extensive minor faulting and occasionally well-developed shear planes. Both of these features are probably due to the movement of an ice-sheet above the shales.

It is only in the *Gangamopteris* sandstones of Stage 2 that contortions of the sediments are developed to an important extent. On the south and east faces of Morton's Quarry in the Bald Hill area, considerable overfoldings and contortions occur, the bedding planes at one part being vertical, though the general dip is to the east at 30 deg. (Figs. 2 and 3). It is possible that some of this contortion was caused by floating ice, but, in the author's opinion, the large scale overfolding seen in the east face of the quarry and much of the contortion can only be explained by the immense pressure exerted by an ice-sheet in overriding the sandstones. Such features are often recorded from the Pleistocene glacial deposits of the Northern Hemisphere.

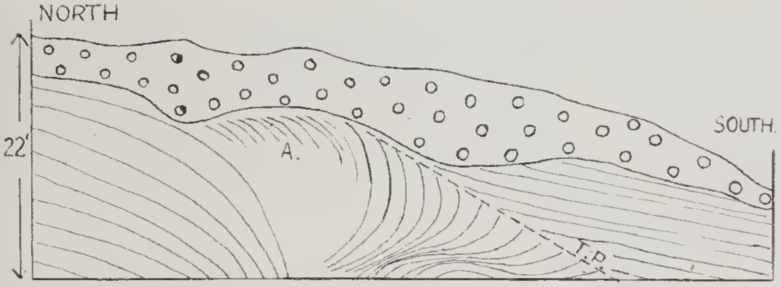

Fig. 2.—Vertical section of main face, Morton's Quarry, Bald Hill area, showing the winnowed tillite overlying *Gangamopteris* sandstones. T.P.=thrust plane (?). Beds are vertical at A.

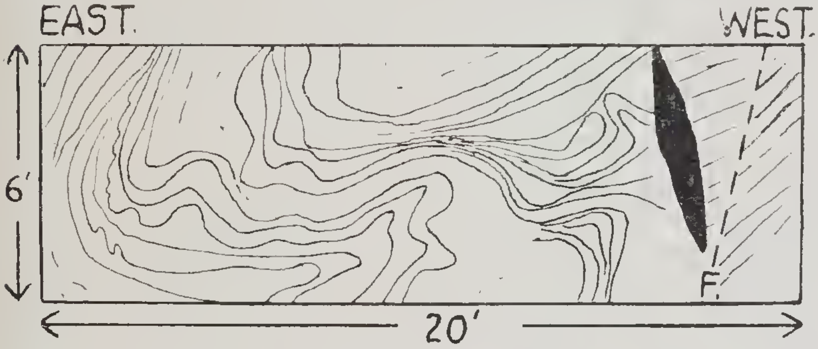

Fig. 3.—Vertical section, south side of Morton's Quarry, Bald Hill area. F.=fault. Black represents injected material (see also Fig. 4).

In the north-west corner of Morton's Quarry, there occurs a striking feature, a vertical section of which is given in Fig. 4. The black part represents a tumultuous mass of large boulders imbedded in a fine-grained matrix, which consists partly of broken fragments of Permian sandstone similar to that found *in situ* elsewhere in the quarry and partly of a material identical in appearance with the matrix of some of the tillites of the North Korkuperrimul area. The boulders themselves are mostly foreign

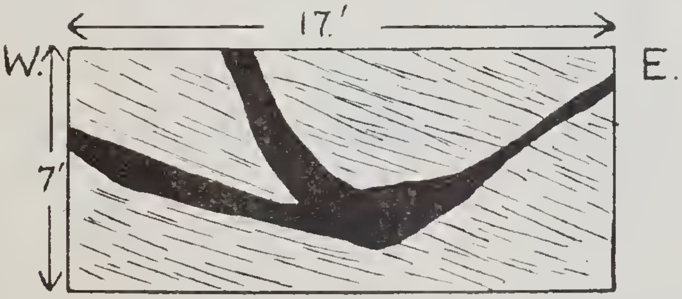

Fig. 4.—Vertical section, north side of Morton's Quarry, Bald Hill area, showing tillitic material (black) injected into sandstones (shaded).

types, including mica-schist, felspar porphyry and many granites, some of which occur as very large blocks. This mass of boulder clay is partly interbedded with the sandstones around it and partly cross-cutting. It can best be explained by postulating that the sandstones were cracked and fissured by the movement above them of an ice-sheet or glacier, which subsequently forced material from the ground moraine into the cracks and fissures so formed.

Glacial Mudstones.

These rocks always pass gradually into well-bedded sediments and occasionally show rude bedding themselves. These facts, coupled with the great thickness and fine grain of the mudstones, seem to indicate a lacustrine origin for them. They were probably formed partly from the material dropped to the bottom of lakes by icebergs detached from glaciers, and partly by the discharge of sub-glacial streams into glacier-dammed lakes (as described by Officer and Hogg, 1894).

In Stages 7 and 9 in the North Korkuperrimul area, where glacial mudstones below grade into tillite above, it seems necessary to postulate that glacial lakes were formed in advance of the approaching ice-sheets or glaciers, and that glacial mudstones were formed in these lakes as suggested above. In some cases, the ice-sheet terminated in the lakes and then tillite and glacial mudstones were formed together, one grading into the other, much as Officer and Hogg (1894) suggested. At other times, the lakes in which the mudstones had formed were either drained or greatly shallowed, with the result that the ice-sheet advanced over the mudstones and deposited tillites above them. In such cases, contortion of the underlying mudstones would have probably occurred. However, the close physical similarity between glacial mudstones and tillite might prevent the line of junction between them from being seen, and the frequent absence of stratification in the glacial mudstones would prevent evidence of contortion from being preserved, i.e., the mudstones may have been complexly mixed up with the ground moraine of the glacier or ice-sheet, but unless they were clearly stratified, no evidence of this phenomenon would be retained.

Englacial Deposits.

According to Chamberlin (1895) and Slater (1926), englacial material occurs as thin interstratified bands and laminae in the ice of a glacier. Boulders are numerous and the laminae of englacial material often curve both below and above them. When the ice melts, the englacial material forms, among other things, deposits of boulder clay, which often preserve the tectonic structures imposed upon the englacial material when it was in the ice of the glacier. The beds of Stage 12 in the North Korkuperrimul area are believed to be englacial deposits, for, though they show distinct stratification in parts, they differ from the mudstones of glacial origin seen elsewhere in the area. For instance, they contain thin sandstone bands (now calcareous) which are sometimes contorted and frequently faulted, and are usually sharply demarcated from the mudstone above and below them. Between these bands, the rock consists of boulder mudstone, generally unstratified, and soft greasy blue-black shale, perfectly laminated and occurring in bands from 1 inch to 1 foot in thickness. Boulders are present in this soft shale, the laminae of the shale curving both above and below them.

Typical Sequence of Deposits, (fig. 5).

Even though glacial mudstones are absent, Stage 10 is the most representative (and complex) in the North Korkuperrimul area. In particular, the cycle of events due to alternate advances and retreats of the glaciers is very well shown. In each cycle, the lowest bed is a tillite, representing an advance of the ice over the area. Almost invariably, the tillite is overlain by conglomerate, which varies greatly in thickness and always shows an exceedingly sharp junction with the tillite below. This is only what would be expected, for immediately the ice-sheet withdrew from the area, streams originating from it would work over the ground moraine which had become exposed. The fine material would be carried away, but the coarser material, including pebbles and boulders, would be soon deposited on the surface of the till. Usually, the junction between conglomerate and till is very straight and sharp; but sometimes it is highly uneven, a feature which is probably explained by the great erosive power of the fast-flowing extra-glacial streams.

The great development of fluviatile deposits following the retreat of the ice-sheets is a typical feature in the Pleistocene glaciation of parts of the United States of America. Salisbury

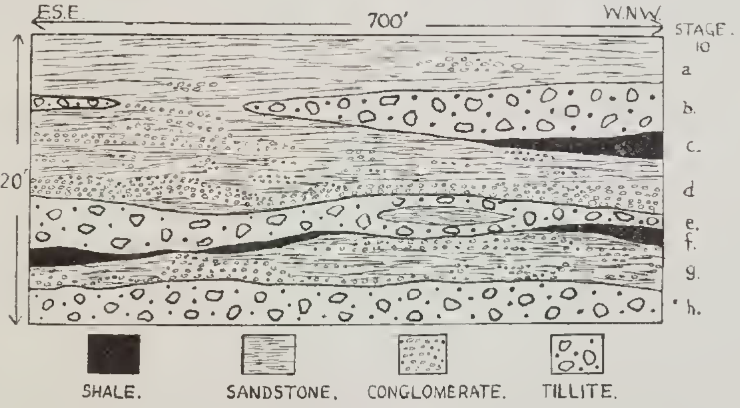

Fig. 5.—Reconstructed vertical section along the strike of the beds of Stage 10, North Korkuperrimul area, showing the extent of lateral and vertical variation.

(1896) has described how a typically braided type of drainage is developed, the streams rapidly alternating between aggradation and degradation, so that a channel is no sooner scoured out of the till than it is filled up with conglomerate and sand and a new channel is formed. It is believed that such extensive "outwash plains" were the usual development in the North Korkuperrimul area following the retreat of the ice.

The conglomerates resting on the tillites grade up into sandstones with gravel bands and occasional lenticles of conglomerate, and the sandstones grade upwards into well laminated shales or finer-grained sandstone. This can best be explained by assuming that the ice-sheet was gradually receding. despite Salisbury's statement (1896) that the deposits of such outwash plains are best developed when the ice-sheet is practically stationary.

As this recession went on, the velocity of an extra-glacial stream at any fixed point on the outwash plain would become smaller and smaller and the material it deposited would be finer and finer, until ultimately at any such point, the ideal sequence of the deposits would be conglomerate at the base, passing up into gravel, then sandstone and finally siltstones or shales.

This sequence, which occurs throughout Stage 10, could also be explained by postulating the incidence of lacustrine conditions soon after the first sandstones were deposited, with gradual deepening of the lake to allow the deposition of the finer sediments. However, while lacustrine conditions were not absent, fluviatile conditions were probably predominant for most of the time between successive advances of the ice.

This cycle of events, as described above, occurs six times in Stage 10 and there is no evidence that repetition of beds by faulting has occurred. Of course, variations do occur, particularly with the tillites, whose variation in thickness (see Fig. 5) may be explained by—

(*a*) irregularities in the sub-tillitic surface and/or

(*b*) differential erosion of the till after the retreat of the ice.

Interglacial Periods.

Since land-ice glaciation probably persisted in the Bacchus Marsh area until the close of the Permian (see Effect on associated sediments, page 122), the sandstones of Stage 2 (*Gangamopteris* sandstones) may represent an interglacial period, for the presence of *Gangamopteris* leaves and the large amount of carbonaceous material and fossil wood in these sandstones shows that land vegetation was well established by this time. Nowhere else in the Permian of this area have plant remains been found, except for the carbonaceous material in the sandstones of Stage 11, which may mark an earlier interglacial period.

The Older Volcanics.

By R. JACOBSON, M.Sc.

The Older Volcanic lavas extend for several square miles over the Pentland Hills and Bald Hill. The series comprises both basalts and ultra-basic lavas, and therefore the term "Older Volcanic," as used by the Geological Survey of Victoria under A. R. C. Selwyn, is considered preferable to "Older Basalts." Between the two main areas of Permo-Carboniferous rocks the Korkuperrimul Creek flows almost entirely in Older Volcanics, and the steep-sided valley provides excellent sections for the study of the lavas and their sequence (see Fig. 7).

BASALTIC LAVAS.

Olivine Basalts with Magnesia-Rich Glass.

This group of lavas is characterized by phenocrysts of partially serpentinized olivine, and a base which consists of magnesia-rich glass and serpentine. For convenience these lavas are henceforth referred to as the "serpentine basalts." Their distribution is shown in Figure 1. There are usually about three flows of serpentine basalt resting on the Permo-Carboniferous at the base of the Older Volcanic series. One of these flows at Section E contains a certain amount of analcite.

In hand-specimens the serpentine basalts are generally greenish-black in colour, with numerous brownish-green phenocrysts of olivine. Microscopically [5077], Sect. C, No. 2, (numbers in brackets refer to slides in the University collection, and descriptions of the character—Sect. C, No. 2—refer to localities shown in Figure 6) is a medium grained serpentine basalt characterized by phenocrysts of olivine only, with a mero-crystalline groundmass composed mostly of plagioclase, together with pyroxene, iron-ore, and a residual serpentine-glass base. In this rock the texture is intersertal-intergranular (Pl. VIII., fig. 3), but in coarser grained types, such as [5084], Sect. D, No. 1, there is a distinct tendency for the transition from the intergranular to the ophitic type of texture. The olivine phenocrysts, up to 2.5 mm. in diameter, are generally resorbed, and invariably partly serpentinized. Only a few small granules of olivine occur, and these probably do not represent a true groundmass generation of olivine. Iddingsite is absent.

Narrow crowded laths of labradorite (Ab. 40), forming about 60 per cent. of the groundmass, average about 0.3 mm. in length, and usually show a slight flow structure around the olivine phenocrysts. The pyroxene is intergranular, and occurs as pale brown to almost colourless prisms which average 0.05 mm. in length. A violet tinge indicates that it is slightly titaniferous. The iron-ore is coarse grained, and as determined on a polished section, consists mostly of skeletal-octahedral plates of magnetite,

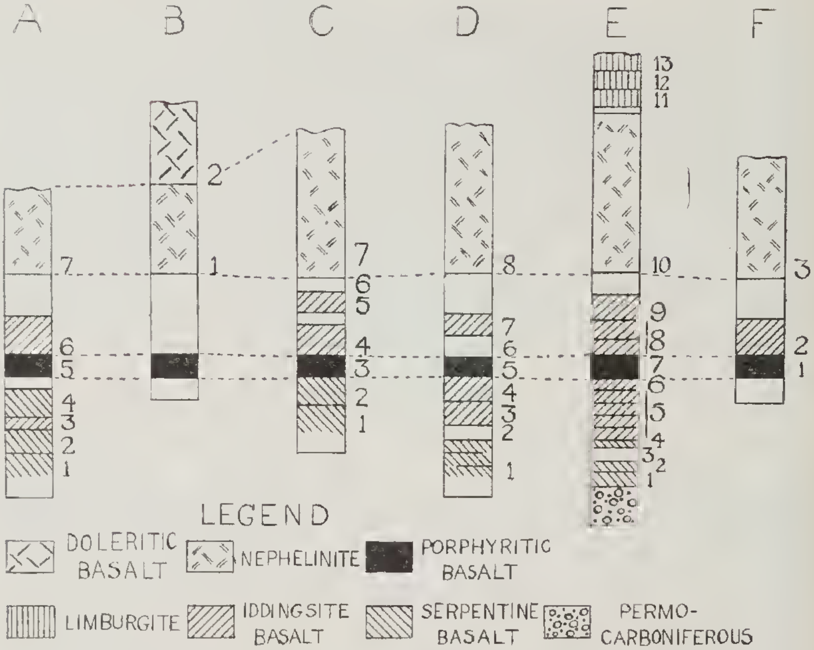

Fig 6.—Shows the detailed lava sequence at six localities, Sections A to F, shown on the map. Approximate vertical scale, 0.66 inches equals 100 feet.

with a few laths of ilmenite. The magnetite is sometimes moulded on pyroxene or felspar. Apatite is not abundant, while occasional small flakes of biotite are associated with the iron-ore. A little secondary calcite is also present. The magnesia-rich mesostasis occurs in intersertal wedges which consist of a mixture of pale green glass, and a pale green micro-crystalline serpentine with a fibrous and micro-radiate structure. This serpentine is faintly pleochroic from green to yellow, has a fairly high double refraction (first order reds and greens), and a refractive index greater than that of labradorite. The serpentinization of these basalts has probably been due to a late-magmatic tendency towards the concentration of magnesia and water in the residual liquid.

A Serpentine-Analcite-Basalt.—This basalt [5092], Sect. E, No. 1, contains abundant phenocrysts of altered olivine, the cores of which consist of an unusual type of iddingsite, and the rims of pleochroic serpentine. The iddingsite is pleochroic from green to yellow, and has a higher double refraction than usual. A moderate amount of limpid analcite occurs in irregular patches in the serpentine-glass mesostasis. It has a good cleavage, and is mostly isotropic, but in part shows low double refraction. The analcitization was probably brought about by a local late-magmatic process.

The Porphyritic Basalt.

Overlying the serpentine basalts is a thin persistent flow of porphyritic basalt. The coarse grain, and porphyritic texture of this rock, permit ready identification in the field, so that it can be used as a "marker flow." There are two varieties, one crowded with phenocrysts of both pyroxene and plagioclase, the other with numerous phenocrysts of plagioclase, but few large pyroxenes. The rock when fresh is dense and dark coloured, but weathering etches out the phenocrysts of pyroxene and plagioclase.

The specimen selected for analysis, [5079], Sect. C, No. 3, contains numerous phenocrysts of pyroxene and plagioclase, and a few smaller olivines. The mero-crystalline groundmass, which is subordinate to the phenocrysts, consists of plagioclase, augite, iron ore, apatite and a little intersertal glass. The phenocrysts of plagioclase, averaging 5 mm. in diameter, are tabular parallel to (010). As shown by the albite twinning, the plagioclase laths have a divergent interleaved structure (Pl. VIII., fig. 2), with small inclusions of glass and wedge-shaped crystals of pyroxene. Narrow films of green glass, crowded with apatite and feathery iron ore, sometimes occur between the twin lamellae and along the cleavage planes. Sometimes the inclusions have been injected along secondary fractures produced by flow movements of the partially crystallized lava. The plagioclase is strongly zoned in sections parallel to (010), the composition ranging from bytownite (Ab. 25) at the core, to andesine (Ab. 60) at the rim.

The composite, prismatic phenocrysts of titaniferous augite are idiomorphic, but sometimes partially enclose small plagioclase laths around the margins. The rims of the pyroxene phenocrysts are deep violet-brown in colour, and faintly pleochroic, with X, Z; yellow-brown, and Y; violet-brown. Polysynthetic twinning on (100), shown by narrow diagonal bands across the crystal, sometimes occurs. The resorbed, glomeroporphyritic, partially serpentinized olivine phenocrysts are subordinate to pyroxene and plagioclase.

The coarse grained groundmass consists of violet-brown titan-augite, plagioclase, apatite and abundant iron-ore. The iron-ore is coarse grained, and as determined on a polished section, consists of skeletal-octahedral plates of magnetite, and simple laths of ilmenite. The magnetite is often moulded on pyroxene or felspar. Stout needles of apatite are very numerous, but biotite is uncommon. The intersertal mesostasis, crowded with apatite and iron-ore, consists partly of green or orange coloured glass, and partly of serpentine. Occasional amygdales, filled with zeolites, calcite or serpentine, also occur.

Another specimen [5078] of the porphyritic basalt from Sect. C differs from the one described above in having the olivine phenocrysts completely iddingsitized. [5088], Sect. D, No. 5, is a rock crowded with plagioclase phenocrysts, while olivine and pyroxene, which are often glomeroporphyritic, are less common and smaller in size. The groundmass is coarse grained and almost holocrystalline. Large apatite crystals, up to 1 mm. in length, are common in this rock.

The Iddingsite Basalts.

Numerous flows of iddingsite basalt occur in this Older Volcanic series. They occur mostly above, but also below the porphyritic basalt, and as a group are characterized by phenocrysts of iddingsitized olivine. Minor variations in grain size, in the proportion of pyroxene to felspar, and also in the amount of glass present, occur among the lavas of this group.

In the hand-specimen the iddingsite basalts may be recognized by glassy red phenocrysts of olivine, which become brown when the rock is weathered. The rock [5081] from Sect. C, No. 5, is a coarse grained iddingsite basalt characterized by large olivine phenocrysts rimmed with iddingsite, set in a coarse grained mero-crystalline groundmass composed of plagioclase, intergranular pyroxene, iron-ore, apatite, a little biotite and a residual intersertal glass. The texture is intersertal-intergranular. The sporadic, slightly resorbed olivine phenocrysts, up to 2.5 mm. in length, are surrounded by conspicuous rims of red iddingsite. They are often glomeroporphyritic, with the individual crystals united by the iddingsite rims. In addition to the iddingsitized olivine phenocrysts, a few small crystals of non-iddingsitized olivine occur in the groundmass, indicating that the groundmass generation of olivine crystallized after iddingsitization had ceased. Only occasional micro-phenocrysts of pyroxene occur in this rock, but in [5108], Sect. F, No. 2, pyroxene phenocrysts are more abundant, occurring glomeroporphyritically with olivine in groups up to 5 mm. in diameter.

The groundmass pyroxene, a pale violet-brown, slightly titaniferous augite, is only approximately intergranular. The labradorite laths (Ab. 45), which are tabular and strongly zoned in sections parallel to (010), are fairly even in size, and average 0.5 mm. in length. Sometimes, as in [5108], the cores of the laths are altered to a fawn coloured cryptocrystalline saussurite. Apatite is common, while a little biotite is associated with the hypidiomorphic iron-ores, which consist of laths of ilmenite and plates of magnetite. An intersertal, yellow, green or orange coloured mesostasis, consisting of glass and a little serpentine, is fairly abundant. In [5074], Sect. A, No. 6, the mesostasis consists of glass, zeolites and serpentine.

[5080], Sect. C, No. 4, is a medium grained iddingsite basalt, which differs from the coarse grained type described above, in that the groundmass is finer in grain, and the large sporadic phenocrysts of olivine are replaced by numerous micro-phenocrysts.

[5090], Sect. D, No. 7, is a fine grained iddingsite basalt with a few large phenocrysts of olivine and pyroxene, and occasional micro-phenocrysts of plagioclase, set in a fine grained groundmass composed mostly of pyroxene and plagioclase, together with magnetite, apatite and a little interstitial glass. The plagioclase laths show flow structure, especially around the olivine phenocrysts.

[5087], Sect. D, No. 4, is a rock with abundant olivine phenocrysts rimmed with iddingsite, and occasional micro-phenocrysts of pyroxene and plagioclase, set in a glassy groundmass which is comparatively poor in felspar. Brown glass and stellate clots of titaniferous augite fill the interspaces in the open felspar mesh. The glass, which is crowded with apatite and brownish skeletal crystals, forms about 30 per cent. of the groundmass. There are also a number of rounded patches of zeolites, often bordered with tangentially arranged pyroxene prisms.

The Doleritic Basalt.

The term "doleritic basalt" has been reserved for a type of basalt with an ophitic texture and richly titaniferous pyroxene. At Section B (on the west bank of the Korkuperrimul Creek) a thick flow of doleritic basalt overlies the nephelinite, but further to the south it is faulted against the nephelinite which caps the hill above Section A. This doleritic basalt can be traced for half a mile to the west of the Korkuperrimul Creek.

In the hand specimen the doleritic basalt is medium grained and grey-black in colour, with olivine phenocrysts and glassy felspar visible under a lens. Under the microscope, the rock [5076], Sect. B, No. 2, is a medium grained olivine basalt characterized by its ophitic texture (Pl. VIII., fig. 1). It is holocrystalline and lacks a distinct groundmass. The resorbed olivine phenocrysts, up to 1.5 mm. in length, together with smaller granules, are only slightly iddingsitized. Titan-augite occurs as large allotriomorphic plates up to 1.5 mm. in length, intergrown ophitically with the plagioclase. Sections normal to (010) are strongly pleochroic, with X, Z; yellow-brown, and Y; reddish-violet. Labradorite (Ab. 45) occurs as tabular laths up to 1 mm. in length, but averaging half this size.

The iron-ores, as determined on polished sections, consist of large skeletal-octahedral plates of magnetite, laths of ilmenite and a small amount of pyrite. The magnetite is often moulded on pyroxene or felspar. Apatite occurs as stout needles up to 0.5 mm. in length, while a small amount of biotite is associated with the iron-ore. The intersertal base, consisting mostly of zeolites, is not very abundant. The rock [5124] from the fault junction just north of Section A is similar to the one described above, except that the olivine phenocrysts are rimmed with deep red iddingsite, and the base is more glassy.

Tachylyte Flows.

Small flows of tachylyte are found at Dyke Cliff, and also along Morton's Creek, but in a gully on the western slopes of Bald Hill, a tachylyte flow, which is interbedded with a series of decomposed lavas, has a thickness of about 15 inches, and can be traced for a distance of about 100 yards. As these tachylytes are interbedded with the nephelinites they may be alkaline-ultra-basic and not basaltic in composition, but whether basaltic or ultra-basic glasses, flows of such dimensions are unusual. The flows are well jointed, and weather out as a line of rounded nodules. In the hand-specimen the glass is dense, brittle and dark brown in colour, with a vitreous to resinous lustre. Tiny crystals of olivine are the only phenocrysts visible.

Under the microscope, the tachylyte [5140] is seen to contain small idiomorphic phenocrysts of olivine, up to 1 mm. in length, which often have complex outlines and inclusions of glass. Some of the smaller crystals are skeletal in outline. A small xenocryst of olivine, surrounded by a reaction rim of granular olivine, also occurs. The glass is orange-red to yellow in colour according to the thickness of the section, and contains numerous perlitic fractures. It has a refractive index greater than 1.530, and is mostly isotropic, but occasionally cryptocrystalline. Flow lines, marked by brownish dust-like inclusions, are especially noticeable around the phenocrysts. A small lenticle of colourless glass, containing a few fragments of xenocrystic quartz, also occurs.

ULTRA-BASIC LAVAS.

These include the following groups:—

- The olivine nephelinites—
  - (*a*) Felspar-free.
  - (*b*) With accessory felspar.
  - (*c*) The nepheline limburgites.
- The limburgites.
- The limburgite-basalts.

The limburgites and limburgite-basalts represent separate flows overlying the nephelinites, but the sub-varieties of the olivine nephelinites, namely the felspar-free nephelinite, the nephelinite with accessory acid plagioclase, and the nepheline limburgites, are not usually represented by separate flows, but are merely lateral variations in massive nephelinite flows. Three limburgite flows occur at Section E, and the limburgite-basalts occur at three points on the Pentland Hills (see map), but as the extent of these flows is unknown, no distinction between these lavas and the nephelinites is made on the map. The total area mapped as olivine nephelinite is about 3½ square miles, and comprises the higher parts of the Pentland Hills, and also Bald Hill. The olivine nephelinite commonly occurs as massive columnar flows of considerable thickness. At Bald Hill the individual flows are comparatively thin, but eleswhere the nephelinite capping probably consists only of one or two flows. The columnar jointing is somewhat irregular, with individual columns up to 6 feet in diameter. As the massive nephelinites offer greater resistance to erosion than the basaltic lavas, the edges of the tilted nephelinite flows stand out as rocky ridges, and small waterfalls occur where the nephelinites cross the Korkuperrimul Creek. In the hand-specimen the nephelinites and limburgites are extremely fine grained brownish or grey-black coloured rocks with numerous phenocrysts of glassy olivine. Olivine-enstatite xenoliths are locally abundant.

The Olivine Nephelinites.

The olivine nephelinite flows show a certain amount of lateral variation with regard to the amount of nepheline and glass present, the presence or absence of accessory acid plagioclase, the abundance of pyroxene phenocrysts and the degree of iddingsitization of the olivine.

(*a*) *The Felspar-free Nephelinites.*

The specimen selected for analysis [5110] was collected from a columnar flow, about 50 yards from the head of a small gully on the western slopes of Bald Hill. It is a porphyritic rock with abundant phenocrysts of olivine and occasional micro-phenocrysts of pyroxene, set in a fine grained groundmass composed of pyroxene, nepheline, iron-ore, apatite, a little biotite and a small amount of residual glass. Felspar is absent. The olivine phenocrysts, which rarely exceed 2 mm. in diameter, are usually considerably resorbed, and only slightly iddingsitized. Micro-phenocrysts of pale violet-brown, weakly titaniferous augite are rare, but tiny prisms of a similar pyroxene, averaging 0.05 mm. in length, form about 60 per cent. of the groundmass. A violet tinge and faint pleochroism in sections normal to (010), with X, Z; yellow-brown, and Y; violet, indicate the weakly titaniferous nature of this pyroxene.

Allotriomorphic plates of interstitial nepheline, which average 0.08 mm. in diameter, and which often contain small inclusions of pyroxene and apatite, form about 10 per cent. of the rock. Although the nepheline is rarely idiomorphic, it shows a distinct prismatic cleavage to which the extinction is parallel, and is often moulded on small crystals of olivine, in such a way that they both extinguish in approximately the same position. These plates (Pl. 2, Fig. 4) are sometimes nearly 1 mm. in diameter. Granular iron-ore, mostly magnetite with a little ilmenite, is fairly abundant, while micro-segregations of granular olivine, iddingsite and iron-ore are not uncommon. Flakes of deep red-brown biotite are scattered through the groundmass, sometimes associated with the iron-ore, but also with small patches of sodic zeolites. In the latter case both red and green biotite occur. and the inner ends of projecting pyroxene crystals are rimmed with aegirine. Idiomorphic needles and prisms of apatite, strewn through the nepheline and glass, are abundant. A little interstitial glass, and occasional patches of zeolites (natrolite?), usually with a rim of yellow glass, complete the base of the rock.

A specimen [5111], from the top flow of a cliff just north of Dyke Cliff, is a type in which the olivine phenocrysts are surrounded by wide rims of red-brown iddingsite, and which contains, in addition to magnetite, a little red-brown or greenish picotite with a reaction rim of magnetite. A thin flow of olivine nephelinite [5112], which underlies the main nephelinite flow in Morton's Creek, is a fine-grained type which contains iddingsitized olivine phenocrysts, and small stout ragged laths of micro-phenocrystic nepheline. In [5075], Sect. A, No. 7, a few of the idiomorphic pyroxene phenocrysts are moulded on a core of resorbed olivine.

(*b*) *The Nephelinite with Accessory Felspar.*

A specimen selected as typical of this variation [5083] was collected from the base of flow No. 7, Sect. C. Three hundred yards to the south the base of this same flow is a felspar-free olivine nephelinite. The rock contains phenocrysts of partially iddingsitized olivine, and a few small phenocrysts of zoned pyroxene with titaniferous rims and spongy greenish cores. The fine-grained groundmass consists of pyroxene, nepheline, magnetite, ilmenite and chromite, together with colourless veinlets consisting of a mixture of felspar, nepheline, and small patches of glass and zeolites. The felspar shows broad twin lamellae, and sometimes a fine cross hatching suggestive of anorthoclase, but as its refractive index is less than that of nepheline, it is probably an acid plagioclase, possibly oligoclase.

(*c*) *The Nepheline Limburgites.*

A specimen selected as typical of this variation was collected from a columnar outcrop a quarter of a mile to the south of the east end of Mier's Cliff. The rock [5119] and [5120] is really a basic olivine nephelinite as it is relatively poor in nepheline and rich in pyroxene, and as such is closely related to the limburgites. Laterally, with the increase in nepheline, the rock grades into the normal olivine nephelinite. It contains conspicuous phenocrysts of orange-red iddingsite, which are faintly pleochroic and slightly zoned, and occasional micro-phenocrysts of titaniferous augite, set in a fine-grained groundmass composed largely of augite (80 to 90 per cent.), together with subordinate nepheline, iron-ore, apatite, a little glass and veinlets of zeolitic and felspathic materials.

The Limburgites.

Three limburgite flows, each about 20 feet in thickness, overlie the nephelinites at Section E. They dip downstream at a small angle on the west bank of the Korkuperrimul Creek. The lowest flow [5104], Sect. E, No. 11, is a typical limburgite, with phenocrysts of olivine and micro-phenocrysts of pyroxene embedded in a fine-grained groundmass composed mostly of pyroxene, glass and iron-ore. Felspar is absent. Resorbed olivine phenocrysts, rimmed with yellow-brown iddingsite, are fairly abundant. One large phenocryst consists of a core of iddingsite surrounded by a border of olivine, which in turn is rimmed with iddingsite (Pl. VIII., fig. 6), indicating two distinct periods of iddingsitization. The micro-phenocrysts of weakly titaniferous augite are not abundant, and in several cases consist of rims surrounding olivine xenocrysts.

The groundmass is composed almost entirely of pyroxene and glass in approximately equal proportions. The hypidiomorphic, pale violet-brown prisms of titaniferous augite average 0.02 mm. in length, and show faint pleochroism in sections normal to (010). Granular magnetite is abundant, apatite is rare, while a little picotite with a reaction rim of magnetite also occurs. A dark-brown interstitial glass, crowded with skeletal crystals, forms a considerable proportion of the base, while patches of colourless glass and zeolites are locally abundant.

The upper limburgite flow [5106], Sect. E, No. 13, contains more iddingsitized olivine, while the groundmass is composed mostly of pyroxene and interstitial glass, with accessory nepheline and acid plagioclase. The centre flow [5105], Sect. E, No. 12, is coarser in grain, and the groundmass contains a moderate amount of plagioclase. The plagioclase, which occurs in veinlets, is probably andesine.

The Limburgite-Basalts.

The limburgite-basalts overlie the nephelinites at three different points on the Pentland Hills, but the extent of these flows is unknown. The most westerly limburgite-basalt is possibly intrusive into the nephelinite. The first [5122] is situated near the summit of the Pentland Hills, half a mile to the west of the Korkuperrimul Creek (see map). It is a typical limburgite-basalt with micro-phenocrysts of olivine and pyroxene set in a fine-grained groundmass composed of pyroxene and glass, with subordinate plagioclase, iron-ore and apatite. The olivine and pyroxene micro-phenocrysts, which are occasionally glomeroporphyritic, rarely exceed 0.5 mm. in diameter, and are invariably idiomorphic. Sometimes the pyroxene micro-phenocrysts are zoned, and consist of greenish cores of (?) aegirine-augite and rims of titan-augite. The groundmass is composed chiefly of dark-brown glass and crowded prisms of brown augite, averaging less than 0.02 mm. in length, together with subordinate microlites of plagioclase, granular iron-ore and apatite. Occasional patches of zeolites also occur.

The most westerly outcrop [5121] contains abundant phenocrysts of both olivine and augite, set in a fine-grained groundmass consisting largely of augite, glass and iron-ore, together with subordinate plagioclase and nepheline. The plagioclase and hypidiomorphic nepheline are unevenly distributed. In the third limburgite-basalt [5123], which occurs half a mile south of Cockatoo Gully, the olivine and pyroxene phenocrysts are larger and more abundant, the olivine is iddingsitized, and the groundmass is even finer in grain. The bulk of the groundmass consists of tiny prisms of augite and interstitial glass. Iron-ore is unusually abundant, while picotite and apatite are rare. The plagioclase occurs mostly as scattered microlites, but is occasionally microphenocrystic.

Segregation and Xenoliths.

Small rounded micro-segregations of granular olivine [5075], and less frequently pyroxene [5124], are characteristic of all the nephelinite lavas. These segregations are seldom numerous, but one or two occur in almost every slide examined. Sometimes a corroded xenocryst of olivine occupies the core of the xenolith [5142]. Another type of micro-segregation, [5111], consists of granular iddingsite and magnetite.

Olivine-enstatite xenoliths are distributed irregularly through the nephelinite lavas. They are sometimes abundant, with individual nodules up to 6 inches in diameter. As they are rounded in shape and consist of high temperature minerals, olivine, enstatite and picotite, they are probably xenocrystic in origin. Similar xenoliths, containing olivine, diopside and spinel, have been described from the Carboniferous analcite-basalts of Scotland (Memoir No. 33, Geol. Surv. Scot., 1910). Microscopically, the xenoliths [5141] consist mostly of olivine, with moderate amounts of enstatite and picotite. Many of the allotriomorphic grains of olivine, which average 2 mm. in diameter, show a lamellar pseudo-twinning. The lamellae, which are broad and parallel, extinguish in slightly different positions, and have probably been set up by mechanical stress during the grinding-down process. The enstatite is allotriomorphic, and has a good rectangular cleavage. The brown picotite, which occurs in irregular veins between the grains of olivine and enstatite, sometimes shows an octahedral cleavage, and a slight reaction rim of magnetite.

A small xenolith of olivine-free gabbro [5143] was found in the nephelinite dyke at Dyke Cliff. It consists of allotriomorphic grains of bytownite (Ab. 22), averaging 2 mm. in diameter, and allotriomorphic grains of augite averaging half this size, together with a few large grains of apatite and magnetite. The plagioclase is twinned, but only slightly zoned. Most of the augite is brown, but certain irregular zones are strongly pleochroic from red-brown to green. At the junction with the dyke rock, a reaction zone composed of plagioclase and zeolites occurs, while occasional zeolitic veins, derived from the dyke rock, penetrate the xenolith.

Small rounded xenocrysts of quartz are often found in the basalts [5086], nephelinites [5110] and dyke rocks. They rarely exceed 1 mm. in diameter, and are invariably surrounded by a reaction rim. This consist of an inner rim of glass adjacent to the quartz, and an outer zone of pyroxene. The pyroxene, which is diopsidic, is arranged normal to the quartz. Occasionally the ends of the pyroxene prisms nearer the quartz are rimmed with aegirine. A small xenolith of tillite, composed of angular fragments of quartz set in a fine matrix, was found in one basalt [5137]. These inclusions of quartz and tillite represent pieces of country rock picked up during extrusion.

THE LAVA SEQUENCE.

The lava sequence was worked out along the Korkuperrimul Creek. Figure 7, a diagrammatic section showing the sequence of the Older Volcanics along the Korkuperrimul Creek, is based on a correlation of the detailed sequences at Sections A, B, C, D, E and F (see Fig. 6, p. 128). It is impossible to correlate directly the individual flows of the above Sections, because the flows thin out laterally and give place to others, which are usually, but not always, of a similar type. However certain generalisations can be made. (1) The serpentine basalts occur at the base of the series resting on the Permo-Carboniferous. They are all similar in type. (2) A single persistent flow of porphyritic basalt overlies the serpentine basalts. (3) The iddingsite basalts occur mostly above, but also below the porphyritic basalt, but never at the very base of the series. These basalts present numerous minor variations in type. (4) The olivine nephelinites, limburgites and limburgite-basalts always overlie the serpentine, iddingsite and porphyritic basalts. The limburgites and limburgite-basalts overlie the nephelinites, but their relationship to each other, and to the doleritic basalt, are uncertain, as the boundaries of these flows cannot be traced. (5) The doleritic basalt at Section B overlies the nephelinite. It is also highly probable that the doleritic basalts overlie the limburgites and limburgite-basalts. (6) The only evidence as to the relative ages of the dykes and lavas is a case where a monchiquite is intrusive into the basalts below the nephelinite, but not into the nephelinite itself. Thus the general sequence of the Older Volcanics along the Korkuperrimul Creek (see Fig. 7) is as follows:—

7. Doleritic basalts.
6. Limburgites and limburgite-basalts.
5. Olivine nephelinites.
4. Monchiquite dykes.
3. Iddingsite basalts (also below 2).
2. Porphyritic basalt.
1. Serpentine basalts.
    Permo-Carboniferous.

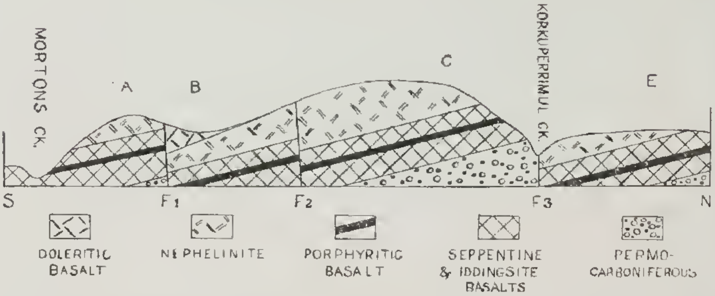

Fig. 7.—A diagrammatic north-south section showing the Older Basalt lava sequence along the Korkuperrimul Creek. The faults F_1, F_2 and F_3 are described on pages 112–113. The length of the section is approximately 1¾ miles.

The lava sequences to the east and west of the Korkuperrimul Creek do not always conform to that described above. Thus south of Morton's Creek, doleritic and iddingsite basalts, which probably overlie the lavas of the Korkuperrimul Creek sequence, occur.

Dip and Thickness of the Lavas.

The Older Volcanic series have a small regional tilt to the south-south-west, but in certain localities, especially in the neighbourhood of large faults, both the amount and direction of tilting varies. Along the Korkuperrimul Creek, between Sections A and C, the lavas are tilted to the south-south-west at about 12 deg., but further north, on the upthrow side of the Pentland Hills fault, the nephelinite dips to the south-west at 20-25 deg., while the overlying limburgites are almost horizontal. Along the Greendale fault, where the Older Volcanics are faulted against the Ordovician, the general dip is south-easterly.

The calculation of the thickness of the Older Volcanic series is complicated by the variations of dip, faulting and lateral thinning of flows. Along the Korkuperrimul Creek (see Fig. 7) the estimated thicknesses are as follows:—

3. Doleritic basalts	150 feet.
2. Nephelinite group	225 feet.
1. Serpentine, iddingsite and porphyritic basalts ..	150–200 feet.
Total	525–575 feet.

Thus the thickness of the Older Volcanic lavas along the Korkuperrimul Creek is at least 525 feet. A series of doleritic and iddingsite basalts, which occur in the south-west corner of the area, and which probably overlie the lavas of the Korkuperrimul Creek sequence, may add considerably to the total thickness of the Older Volcanic series.

Decomposition of the Lavas, and the Origin of the Red Clay Beds.

A striking feature of the Older Volcanic series along the Korkuperrimul Creek is the alternation of decomposed flows with others which show little sign of alteration. The alternation is probably controlled by structural features, such as jointing and tilting. The closely-spaced tabular jointing and the vesicularity of the margins of the flows, and the circulation of the underground waters along the junction planes between the flows results in the decomposition of the flows from the top downwards. As weathering proceeds, the columnar structure is destroyed, and the rock consists of a mass of crumbly semi-decomposed basalt, studded and veined with secondary carbonates, in which occasional nodules of fresh basalt are embedded.

Carbonates are a common product of decomposition of the lavas. They are especially well developed in a small gully on the western slopes of Bald Hill. Earthy magnesite occurs as irregular veins through the decomposed basalt, and also as sheets along joint and fault planes. Secondary calcite occurs in nodules, vesicles and irregular veins through the decomposed rock.

The occurrence of a bright red clay as an irregular layer along the upper margin of a decomposed flow, or as a continuous layer, up to 30 feet or so in thickness, between two solid lava flows, is a common feature of the Older Volcanics along the Korkuperrimul Creek, and also at Myrniong, Flinders and Phillip Island. The material is a closely-jointed, soft, brittle, waxy clay-like substance. The colour of the material is bright red or reddish-brown. The prismoidal jointing is very well developed (especially along the seashore at Flinders). The closely-spaced, more or less vertical joint sets intersect at an acute angle, while a third horizontal set is less prominent. Numerous irregular closed fractures also occur.

A partial analysis shows that, if the material was originally basaltic, considerable chemical alteration has taken place (see Table No. 2).

TABLE NO. 2.

—	1.	2.	3.
SiO_2	26·01	34·45	43·82
Al_2O_3	28·27	17·37	28·76
Fe_2O_3	22·38	23·08	2·66
FeO	0·57		0·20
MgO	1·55	3·30	0·03
CaO	0·71	..	0·58
Na_2O	..	..	0·90
K_2O	..	..	1·66
H_2O + 110°	12·06	8·27	7·76
CO_2	Tr.	..	0·04
TiO_2	3·03	..	4·75
P_2O_5	Nil	..	0·05
MnO	Tr.	..	..

No. 1 Red clay bed, between flows Nos. 4 and 5, Section C. (R. Jacobson.)
No. 2. Specimen of decomposed basalt from the Bellarine Peninsula. Geol. Surv Rept. 1863.
No. 3. Residual clay decomposed Older Basalt from Royal Park (D McCance.) *Proc Roy. Soc.* Vic., xliv (2), n.s, 1932.

Practically all the CaO, MgO, P_2O_5 and Na_2O have been leached out, while the iron, with most of the FeO converted to Fe_2O_3, has been concentrated along with Al_2O_3 and TiO_2. The water content has been greatly increased, and some silica has been lost. The composition differs from the residual clay derived from the Older Basalt in the Royal Park cutting (see Table No. 2), in the abnormal concentration of iron and in the loss of a greater proportion of the silica. A similar concentration of iron occurs in the red clays associated with the decomposed Older Basalts of the Bellarine Peninsula (see Table No. 2). Microscopically the material is extremely fine grained and mostly isotropic, but occasionally cryptocrystalline. It is a clay mineral, probably with a composition such as hydrated silicate of Al_2O_3 and Fe_2O_3.

The origin of these beds of red clay is uncertain. Selwyn (1854), in addition to describing true volcanic breccias, notes the occurrence of beds of red clay intercalated with the Older Basalt lavas of Flinders, and describes them as beds of volcanic mud. Fenner (1918), when describing the Older Basalts of the Bacchus Marsh area, writes, "Beds of tuff, sometimes bright red, occur in the series, and are to be well seen where the Myrniong-Greendale road crosses the Korobeit Creek." Professor Skeats first drew the attention of the author to the doubt as to the origin of these beds, and later with Dr. Summers assisted the author in the examination of these beds in the field. There are at least three alternative modes of origin of these red clays. They may be decomposed lava flows, pyroclastic rocks or sediments formed in the intervals between the extrusion of the lava flows. Of these three possibilities, the third is very unlikely. In many cases the red clays have a mottled appearance, very suggestive of a pyroclastic rock, such as a volcanic mud, tuff, scoria bed, or volcanic agglomerate. By studying a limited section of these beds one is readily persuaded that these clays are probably pyroclastic in origin, but in many cases they can be traced laterally into decomposed basalts, and occasionally into solid basalt. Red clays with a pyroclastic appearance occur at numerous points along the Korkuperrimul Creek, but the best examples are found at Dyke Cliff, in a gully on the western slopes of Bald Hill, opposite Section C, and along Morton's Creek. The author believes that in the Korkuperrimul Creek area, the evidence points to these red clays being decomposed basalts. The occurrences at Flinders and Myrniong are such that, while the author is by no means satisfied as to their pyroclastic origin, no definite conclusion is drawn.

Petrology of the Dyke Rocks.

About a dozen small dykes were found intruding the Permo-Carboniferous and Older Volcanics. They are generally small, and can be traced for only short distances. These dykes include the following types:—

- MONCHIQUITES—
  - (*a*) Felspar-free monchiquites.
  - (*b*) Felspathic monchiquites.
  - (*c*) Fine-grained monchiquites.
- OLIVINE NEPHELINITES.
- OLIVINE BASALTS.

Monchiquites.

(*a*) Felspar-free Monchiquites.—A small irregular monchiquite dyke, intrusive into the basaltic lavas below the nephelinite, but not into the nephelinite itself, occurs on the south bank of the Korkuperrimul Creek, $\frac{3}{4}$ mile to the west of Cockatoo Gully. This rock [5126] contains abundant phenocrysts of olivine and micro-phenocrysts of pyroxene, set in a fine-grained glassy groundmass composed of augite, iron-ore and a little picotite and biotite. The olivine phenocrysts are generally idiomorphic, but sometimes resorbed. The pyroxene micro-phenocrysts, which are mostly idiomorphic, are strongly zoned with diopsidic cores, and rims of titan-augite. The groundmass pyroxene is a titaniferous augite corresponding in colour and pleochroism with the rims of the phenocrysts. In addition to magnetite and a few grains of reddish picotite, a small segregation of green spinel (pleonaste) also occurs. Occasional scales of biotite are present, but hornblende is absent. A glassy mesostasis, crowded with minute brownish inclusions, forms about half the base of the rock.

Another small monchiquite dyke is intruded through the Permo-Carboniferous on the east bank of the Korkuperrimul Creek, 50 yards north of Anderson's Quarry. The rock [5127] is considerably decomposed. It contains phenocrysts of completely serpentinized olivine, set in a fairly coarse-grained groundmass composed of pyroxene and a greenish glass crowded with laths of strongly pleochroic biotite, apatite and iron-ore. The pale violet-brown augite occurs in laths which average 0.2 mm. in length. Occasional amygdales, filled with calcite and glass, also occur.

(*b*) Felspathic Monchiquites.—Two small monchiquite dykes are intruded through the Permo-Carboniferous on the west bank of the Korkuperrimul Creek, about a quarter of a mile south of Cockatoo Gully. They are typical monchiquites except for the presence of a certain amount of plagioclase. The more northerly of these dykes [5128] contains abundant idiomorphic phenocrysts of both olivine and pyroxene, embedded in a groundmass composed of augite, iron-ore, subordinate plagioclase, brown hornblende, apatite and a glassy mesostasis. The olivine phenocrysts are generally idiomorphic, and sometimes serpentinized. The idiomorphic pyroxene phenocrysts are zoned, with brownish diopsidic cores and rims of titan-augite. The smaller pyroxenes are often grouped stellately. Plagioclase (about Ab. 50) occurs in ragged laths containing numerous inclusions of pyroxene and apatite. Numerous scales of reddish-brown hornblende, which are pleochroic from green to red-brown, are associated with the iron-ore. The base of the rock consists of a glass crowded with minute brownish inclusions and tiny scraps of biotite. Occasional amygdales, filled with glass, calcite and a little analcite, also occur.

The more southerly [5129] is similar, but the pyroxene phenocrysts are more abundant, and the plagioclase is more acid in composition (approximately Ab. 65). The yellowish glass is crowded with scales of biotite, but hornblende is almost absent.

A similar monchiquite dyke [5130], intrusive into the Older Volcanics, occurs in a cliff on the east bank of the Korkuperrimul Creek, about 250 yards north-east of Section C.

Another small decomposed monchiquite dyke [5131], intrusive into the Permo-Carboniferous, is found in the Korkuperrimul Creek 150 yards east of Cockatoo Gully. The pyroxene and olivine phenocrysts are completely serpentinized, while the felspar and glass have recrystallized as a fine admixture of secondary chlorite, calcite and zeolitic products, criss-crossed with flakes of biotite and needles of apatite.

(*c*) Fine-grained Monchiquites.—At Dyke Cliff there are two small, fine-grained monchiquite dykes which act as feeders to a lava flow at the top of the cliff. A number of xenocrysts of plagioclase, up to 3 inches in length, were found in these dykes. They—[5132] and [5133]—contain small phenocrysts of olivine and occasional micro-phenocrysts of pyroxene set in an exceedingly fine-grained groundmass, the bulk of which consists of pyroxene, iron-ore, and interstitial glass, together with subordinate plagioclase and a little apatite. The olivine phenocrysts are rimmed with iddingsite, and are generally resorbed. The brownish pyroxene phenocrysts are weakly titaniferous. The groundmass pyroxene occurs in tiny prisms less than 0.01 mm. in length. Apatite and granular iron-ore are abundant. The plagioclase occurs in ragged laths, and is probably an acid labradorite. Interstitial glass forms a considerable proportion of the base.

The Olivine Nephelinites.

An irregular dyke of olivine nephelinite about 10 feet wide, which can be traced for only a few yards, occurs at Dyke Cliff. Several xenoliths of porphyritic basalt, small clots of olivine, occasional xenocrysts of quartz, and a single xenolith of gabbro, were found in this dyke. The rock [5134] contains abundant phenocrysts of olivine rimmed with iddingsite, and occasional micro-phenocrysts of pyroxene set in a fine-grained groundmass composed chiefly of pyroxene and nepheline, together with iron-ore, apatite, biotite and a little glass. Occasional veinlets of plagioclase and zeolites occur.

Olivine Basalts.

A coarse-grained basaltic dyke [5135] is intrusive into the Permo-Carboniferous on the east bank of the Korkuperrimul Creek, about ¼ mile north of Anderson's Quarry. In the hand specimen it is a decomposed mottled yellow rock. It contains phenocrysts of completely serpentinized olivine, and augite rimmed with titan-augite, set in a coarse-grained mero-crystalline groundmass composed of plagioclase, intergranular pyroxene, iron-ore, apatite, a little hornblende and abundant intersertal glass.

Another basaltic (?) dyke, about 100 feet in width, is intruded into the Permo-Carboniferous on the east bank of the Korkuperrimul Creek, about half a mile south of Cockatoo Gully. Only one nearly vertical junction, which appears to be an intrusive contact, is clearly exposed. As the intrusion does not appear to extend to the east for any great distance, it probably represents a plug, and not a dyke. Under the microscope, the rock [5136] contains numerous phenocrysts of partially serpentinized olivine, and zoned titaniferous pyroxene set in a fine-grained groundmass composed of microlites of plagioclase, subordinate pyroxene, granular iron-ore, together with a little picotite, apatite and biotite. An interstitial glass forms a considerable proportion of the base.

Petrogenesis.

Iddingsitization.

Ross and Shannon (1925) have shown that iddingsite is a definite mineral species, which may be represented by the formula $MgO.Fe_2O_3.3SiO_2.4H_2O$, with CaO replacing MgO in the ratio of 4 : 1, and Al_2O_3 partially replacing Fe_2O_3, which is formed by the metasomatic alteration of olivine under oxidising conditions. The conversion of olivine to iddingsite therefore involves an increase in Fe_2O_3 and H_2O. The process is deuteric, and probably takes place just prior to, or during extrusion, because extrusion leads to the escape of the water vapour. The fact that the iddingsite basalts sometimes have a glassy mesostasis crowded with iron-ores of late formation, is additional evidence of the tendency towards the concentration of iron in the residual liquid—as pointed out by Fenner (1929).

The Older Volcanic series of the Korkuperrimul Creek includes a group of iddingsite basalts. The iddingsite usually occurs as a simple rim, varying from a mere film to a wide border, surrounding the olivine crystal. Sometimes the olivine is completely iddingsitized, in which case it is usually slightly zoned and faintly pleochroic. A zoned phenocryst in one of the limburgites (Pl. VIII., fig. 6), which consists of a core of iddingsite rimmed with olivine, and an outer zone of iddingsite, shows clearly that two distinct periods of iddingsitization sometimes occur. In one of the iddingsite basalts [5081] the olivine phenocrysts are iddingsitized, while the groundmass generation of olivine is only slightly affected, indicating that iddingsitization had practically ceased before the crystallization of the groundmass olivine. When serpentine and iddingsite occur together in the same rock, the former is generally secondary in origin, but a strongly pleochroic type of iddingsite, which occurs in the serpentine-analcite-basalt [5092], is probably a normal type of iddingsite which has been modified by subsequent serpentinization.

Serpentinization.

Serpentine is a common alteration product of olivine, and it is now generally accepted that serpentinization, like iddingsitization, may be the result of a primary late-magmatic process. The serpentine basalts of this series, even when perfectly fresh, are characterized by phenocrysts of olivine which are invariably partially serpentinized, and a residual magnesia-rich mesostasis consisting of a mixture of glass and serpentine. The serpentinization of these basalts was almost certainly the result of some primary late-magmatic process. MacGregor, Bailey and Thomas (1930) have described a similar mesostasis, consisting of chlorite, and less commonly of serpentine and chlorophaeite, in the Carboniferous basalts of North Ayrshire. They have also shown that the groundmass felspar has been partially replaced by chlorite at a late stage in the genesis of the rock. Similarly some of the felspar in the serpentine basalts is partially replaced by serpentine.

TABLE No. 3.

—	1.	2.	3.	4.
SiO_2	46·64	39·79	42·39	41·13
Al_2O_3	15·46	12·11	16·17	15·74
Fe_2O_3	4·49	4·67	4·29	4·02
FeO	7·25	7·87	5·79	7·71
MgO	7·24	12·25	7·66	7·98
CaO	10·80	11·29	11·57	10·48
Na_2O	2·43	2·83	4·26	5·56
K_2O	0·92	1·23	1·46	1·12
H_2O + 110°	1·83	1·79	1·85	2·11
H_2O − 110°	0·89	3·06	0·56	0·58
CO_2	Tr.	Nil	..	..
TiO_2	1·90	1·87	2·13	2·34
P_2O_5	0·32	1·30	1·16	0·54
MnO	0·04	0·02	0·23	0·14
Li_2O	..	..	..	Tr.
Cl	..	..	0·11	Nil
S	..	..	0·13	Nil
BaO	..	..	0·01	Nil
Total	100·21	100·08	100·37	99·45
NORMS.				
Q	..	..	..	..
Or	5·56	7·23	8·62	6·64
Ab	20·44	3·14	11·85	2·26
An	28·63	16·68	21·12	14·61
Ne	..	11·36	12·67	24·32
C	..	..	..	..
di	18·51	24·77	20·57	27·27
hy	3·62	..	..	..
ol	8·75	18·82	8·68	10·23
mg	6·50	6·73	6·22	5·83
il	3·65	3·50	5·06	4·42
hm	..	..	..	..
ap	0·72	3·10	2·76	1·18
cal	..	..	..	..
pyr	..	..	0·24	..

No. 1. Porphyritic basalt, Flow No. 3, Section C. (R. Jacobson.)

No. 2. Olivine nephelinite, a lava flow, 50 yards from the head of a small gully on the western slopes of Bald Hill, Bacchus Marsh. (R. Jacobson.)

No. 3. Olivine nephelinite, plug, 8 chains south of the Greendale Hotel, parish of Blackwood. (A. B. Edwards.) *Proc. Roy. Soc. Vic.*, xlvii (1), n.s., 1934.

No. 4. Olivine nephelinite, plug, in allotment 91, parish of Drouin West. (F. F. Field.) *Proc. Roy. Soc. Vic.*, xliii (2), n.s., 1931.

Serpentinization requires an enrichment of the residual liquid in MgO and H_2O, and consequently primary serpentization probably occurs just prior to, or during, extrusion. Similarly Thomas and Bailey (1924), have suggested that the chloritic material in the Tertiary mugearites of Mull represents a chloritized glassy residuum. Thus in this Older Volcanic series there are two distinct trends in the later stages of crystallization of the basalts, one consisting of a concentration of Fe_2O_3 and H_2O in the residual liquid (iddingsitization), and the other in a concentration of MgO and H_2O in the residual liquid (serpentinization).

Notes on Analyses.

The analysis of the porphyritic basalt (see Table No. 3) shows it to be a normal basalt type. The silica percentage is a trifle lower than usual, and the lime slightly higher, but neither is abnormal.

Apart from the Pentland Hills nephelinite, the Greendale and Drouin plugs are the only other recorded occurrences of olivine nephelinite from Victoria. Of these the Pentland Hills nephelinite more closely resembles the Greendale rock, especially as the pyroxene is titaniferous. The Pentland Hills nephelinite is more basic than the Greendale rock (see Table No. 3); the SiO_2, Al_2O_3 and total alkalies are distinctly lower, while MgO is much higher. The Pentland Hills nephelinite compares very closely with Daly's average limburgite (Daly, 1934), and is even slightly more basic in character. The higher MgO content of the Pentland Hills nephelinite results from a greater abundance of olivine. It is of interest to note that there is a sympathetic variation of Na_2O and Al_2O_3 when the analyses of the Greendale, Dronin, and Pentland Hills nephelinites are compared.

Differentiation.

Kennedy (1933), has advanced the theory that the olivine basalts and tholeiitic basalts (i.e. plateau basalts) represent two distinct types of primary basaltic magma. The olivine basalt magmas give rise to an alkaline line of descent, while calc-alkaline differentiates are derived from the tholeiitic magmas. Lehmann (1928, 1931), and Kennedy (1933) maintain that it is the type of pyroxene which crystallizes that controls the subsequent trend of differentiation, and according to Kennedy this ultimately depends upon the chemical composition of the magma. Calcic pyroxenes, diopside and titan-augite crystallize from olivine basalt magmas, while lime-poor enstatite-augites form in the tholeiitic magmas. In the case of the olivine basalt magma, the early removal of lime and magnesia as calcic pyroxenes, leaves the alumina free to combine with the alkalies to form alkali-felspar, and later felspathoids, thus giving rise to an alkaline line of descent.

Since no tholeiitic basalts (in Kennedy's sense) are present among the lavas of the Korkuperrimul Creek, and as olivine basalts were extruded both before and after the olivine nephelinites, the parent magma of this suite is believed to have been an olivine basalt type. The pyroxenes of these Older Volcanics, as determined by approximate measurements of the optic axial angles (Schwarzmann scale), are lime-rich, and usually titaniferous. The groundmass pyroxenes match the rims of the phenocrysts in colour and pleochroism, and are therefore similar in type. No lime-poor pyroxenes with small optic axial angles (pigeonites), which according to Barth (1931) and Fermor

(1926) are the common groundmass pyroxenes of basalts, were found in these Older Volcanic lavas. In so far as an olivine basalt magma has given rise to an alkaline line of descent, with the crystallization of calcic pyroxenes, this suite is in agreement with Kennedy's interpretation.

The derivation of an olivine nephelinite from a parent olivine basalt magma, may be considered as consisting of two processes, (*a*) the formation of a limburgitic liquid, and (*b*) the concentration of soda.

(*a*) The olivine nephelinites, limburgite-basalts and limburgites are all extremely fine-grained rocks, in which olivine is the only prominent phenocrystic phase. Thus the only solid phase present when extrusion occurred was olivine, and sometimes perhaps a little pyroxene and picotite. In the case of the limburgite-basalts, the olivine phenocrysts are very small and idiomorphic, and therefore it is necessary to explain the formation of liquids corresponding in composition to these ultra-basic lavas. A limburgitic liquid may be formed in the lower levels of a basaltic magma chamber, only by the re-solution of some of the olivine which accumulates in this layer under gravitational control. No "squeezing mechanism" can account for the formation of a limburgitic liquid from a basaltic magma, so that re-solution of olivine at depth would appear to be the only reasonable alternative. The occurrence of numerous xenoliths of olivine, enstatite and picotite in the nephelinites afford evidence of the part played by gravitational differentiation.

(*b*) The introduction and concentration of soda cannot be brought about by the same process as that leading to the formation of the limburgitic liquid, as the concentration of soda and the concentration of lime are independent of each other. The irregular distribution of soda, as shown by the lateral variation in the nephelinite flows, indicates the localized nature of the process bringing about its introduction. The occurrence of a single flow of olivine-analcite-basalt, probably formed by a late-magmatic process, affords further evidence of the localization of the concentration of soda. Some form of "gas streaming process," such as that suggested by Shand (1933), has probably been responsible for the introduction of the soda into the limburgitic liquid. The limburgite-basalts, limburgites and nepheline limburgites are regarded as types that have been formed from the same ultra-basic liquid as the olivine nephelinite, but which have not been enriched in soda to the same extent. The absence at the surface of a complementary differentiate to the nephelinites, such as an olivine-poor basalt or an oligoclase basalt, does not necessarily imply that these do not occur at depth.

Age-Relations and Correlations.

The age of the Older Volcanics cannot be determined precisely in this area. They are clearly post Permo-Carboniferous, and pre-date the major faulting of the Bacchus Marsh area. They are overlain by Tertiary deposits, which have been mapped as Miocene by the Survey, but the plant remains are such that this cannot be regarded as conclusive evidence of the pre-Miocene age of the Older Volcanic series. The Older Volcanics were formerly referred to the Miocene, but in recent years the tendency has been to place them still lower in the Tertiary, mostly in the Oligocene.

The South Gippsland dyke association, described by Edwards (1934), consisting of trachy-andesites, analcite-olivine dolerites, olivine-analcite-dolerites, olivine-analcite-basalts, monchiquites and olivine nephelinites, presents a fairly close parallel to the Older Volcanic suite of the Korkuperrimul Creek; but while the South Gippsland province is characterized by crinanites, the nephelinites are the outstanding feature of the Korkuperrimul Creek area. Some of the monchiquite-basalts of the South Gippsland province are very similar in chemical composition to the Pentland Hills nephelinites. Edwards has shown that the monchiquite dykes of South Gippsland and Central Victoria are similar, and characteristic of the Older Basalt suite, and therefore the monchiquites of the Korkuperrimul Creek area serve to demonstrate further the genetic relationships of this suite to the Older Basalt period of vulcanicity.

Summary and Conclusions.

The so-called Permo-Carboniferous deposits of the Korkuperrimul Creek area are all Upper Permian in age, and form an extensive series with a minimum thickness of 2,103 feet, having a strong regional tilt to the S.S.W. The beds consist of tillites (at least 11 separate horizons), englacial deposits (not common) and a great variety of aqueo-glacial sediments. The latter consist of a well-developed suite of fluvio-glacial shales, sandstones, gravels and conglomerates (outwash plain type of deposits), together with thick beds of lacustrine mudstones. Some of the sandstones and shales are also lacustrine in origin. A study of the erratics and heavy minerals of the sediments shows that the material forming the Permian beds was essentially derived from the Lower Palaeozoic (mainly Ordovician) sediments, though it was not possible to determine the precise locality from which this material was derived.

A series of gently tilted Older Volcanic lavas, at least 550 feet in thickness, occurs along the Korkuperrimul Creek. The lava suite comprises serpentine basalts, iddingsite basalts, porphyritic basalt, doleritic basalts, olivine nephelinites, limburgite-basalts and limburgites. The nephelinites approximately equal the basaltic lavas in proportion. The lava sequence established along the Korkuperrimul Creek is interrupted by several large faults, the most important of which are the Pentland Hills fault and the Bald Hill faults. The dyke rocks associated with the lavas include monchiquites, olivine basalts and occasional olivine nephelinites. Thick beds of red clay, alternating with flows of solid lava, are a prominent feature of the Older Volcanic series, and, although they have the superficial appearance of pyroclastic rocks, they are considered to be decomposed lavas. Although the age cannot be fixed exactly in this area, there is little doubt that the suite is closely related genetically to the other Victorian Older Basalts, especially to those of the South Gippsland province.

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References.

Barth, T. W. F., 1931.—Crystallization of Pyroxenes from Basalts. *Amer. Mineral.*, xvi., No. 5, pp. 195-208.

Boswell, P. G. H., 1933.—On the Mineralogy of Sedimentary Rocks. Thomas Murby and Co., London.

Bowen, N. L., 1928.—The Evolution of the Igneous Rocks. Princeton University Press, Princeton.

Bucher, W. H., 1919.—On Ripples and related Sedimentary Forms. *Amer. Journ. Sci.*, xlvii., pp. 149-210.

Chamberlin, T. C., 1895.—Recent Glacial Studies in Greenland. *Bull. Geol. Soc. Amer.*, vi., pp. 199-220.

Chapman, F., 1927.—Monograph on the Triassic flora of Bald Hill, Bacchus Marsh, Victoria. *Mem. Nat. Mus. Melb.*, vii., pp. 121-156.

Daly, R. A., 1933.—The Igneous Rocks and the Depths of the Earth.

David, T. W. E., 1896.—Evidences of Glacial Action in Australia in Permo-Carboniferous Time. *Q.J.G.S.*, lii., pp. 289-301.

Edwards, A. B., 1934.—Tertiary Dykes and Volcanic Necks of South Gippsland, Victoria. *Proc. Roy. Soc. Vic.*, n.s. xlvii. (1), pp. 112-134.

Fenner, C., 1918.—The Physiography of the Werribee River Area. *Proc. Roy, Soc. Vic.*, n.s., xxxi. (1), pp. 176-313.

Fenner, C. N., 1929.—Crystallization of Basalts. *Amer. Journ. Sci.*, Ser. 5, xviii., pp. 225-253.

Fermor, L. L., 1926.—*Rec. Geol. Surv. India*, Vol. 58.

Geikie, J., 1894.—The Great Ice Age. Edward Stanford, London.

Kennedy, W. Q., 1933.—Trends of Differentiation in Basaltic Magmas. *Amer. Journ. Sci.*, xxv., pp. 239-256.

LEHMANN, E., 1928.—Chemie der Erde, Vol. 5.

————, 1931.—*Min. petr. Mitt.*, xli. (1), pp. 8-57.

MCCANCE, D. M., 1932.—Weathering of the "Older Basalt" of Royal Park. *Proc. Roy. Soc. Vic.*, n.s., xliv. (2), pp. 243-256.

MACGREGOR, A. G., BAILEY, E. B., and THOMAS, H. H., 1930.—The Geology of North Ayrshire. *Memoir Geol. Surv. Scotland*, 2nd Edition, pp. 101, 103, 106, 107, 117, 222, and 309.

OFFICER, G., and HOGG, E. G., 1898.—The Geology of Coimadai, Pt. 2. *Proc. Roy. Soc. Vic.*, n.s., x., pp. 180-203.

ROSS, C. S., and SHANNON, E. V., 1925.—*Proc. U.S. Nat. Mus.*, xxvii., Art. 7.

SALISBURY, R. D., 1896.—Stratified Drift. *Journ. Geol.*, iv. (2), pp. 948-970.

SELWYN, A. R. C., 1854.—On the Geology, Palaeontology, and Mineralogy of the Country situated between Melbourne, Western Port Bay, Cape Schanck, and Point Nepean, accompanied by a Geological Sketch Map and Sections. *Geol. Surv. Vic.*, Prog. Rept., pp. 1-10.

SHAND, S. J., 1933.—The Lavas of Mauritius. *Q.J.G.S.*, lxxxix., pp. 1-13.

SINGLETON, F. A., 1935.—The Triassic Rocks of Victoria. *Handbook for Victoria, A.N.Z.A.A.S.* (Melb.), p. 124.

SKEATS, E. W., 1909.—The Volcanic Rocks of Victoria. *Pres. Addr., Sect. C, A.A.A.S.* (Brisbane), pp. 173-236.

SKEATS, E. W., 1921.—Report of Committee on Alkaline Rocks. *A.A.A.S.* (Hobart), pp. 305-308.

SLATER, G., 1926.—Glacial Tectonics as reflected in Disturbed Drift Deposits, Pt. 1. *Proc. Geol. Assoc.*, xxxvii., pp. 392-400.

SUMMERS, H. S., 1923.—The Geology of the Bacchus Marsh and Coimadai District. *Proc. Pan-Pacific Sci. Cong.* (Australia), pp. 1632-1648.

————, 1935.—The Permo-Carboniferous Rocks of Victoria. *Handbook for Victoria, A.N.Z.A.A.S.* (Melbourne), pp. 120-123.

SUSSMILCH, C. A., and DAVID, T. W. E., 1920.—Sequence, Glaciation, and Correlation of the Carboniferous Rocks of the Hunter River District. *Proc. Roy. Soc. N.S.W.*, liii., pp. 246-338.

SWEET, G., and BRITTLEBANK, C. C., 1893.—The Glacial Deposits of the Bacchus Marsh District. *A.A.A.S.*, pp. 376-389.

THOMAS, H. H., and BAILEY, E. B., 1924.—Tertiary and Post-Tertiary Geology of Mull, Lock Aline, and Oban. *Memoir Geol. Surv. Scotland*, p. 144.

Explanation of Plates.

PLATE VII.

Fig. 1.—Bands of sandstone intercalated in tillite, Werribee River, 1½ miles downstream from the hanging valley. The cliff is at least 40 feet in height.

Fig. 2.—Fault junction (F.6) between basalt and Permian sandstones, Korkuperrimul Creek, west bank, just below the junction with Morton's Creek, Bald Hill area.

Fig. 3.—Tillite (typical), Stage 4 (*c*), North Korkuperrimul area.

Fig. 4.—Sandstones with interbedded conglomerates and gravels, showing their impersistent nature. Stage 6, North Korkuperrimul area.

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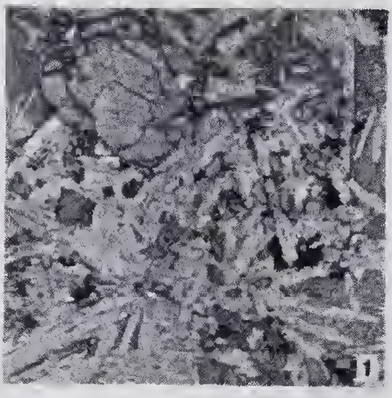
The Permian Rocks.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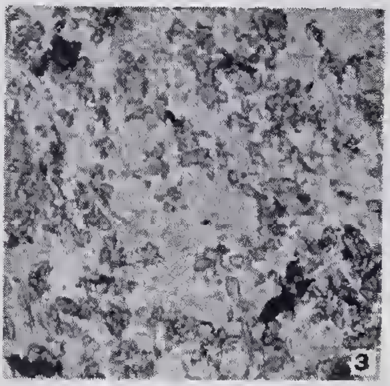
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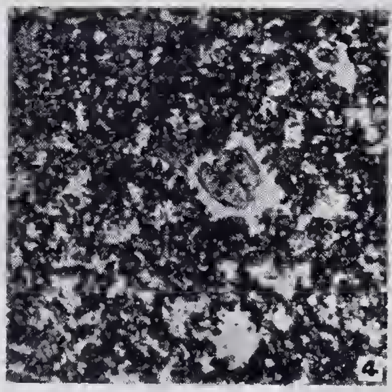
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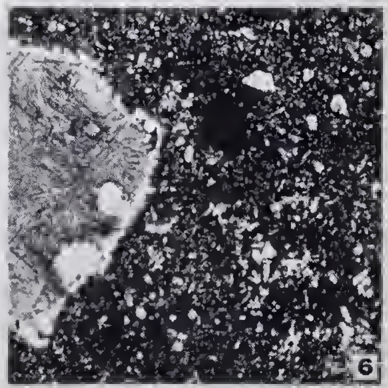
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PLATE VIII.—PHOTOMICROGRAPHS.

1. *Doleritic basalt*, Section B, No. 2. Shows small olivine phenocrysts, large irregular plates of ophitic pyroxene, and the lack of a distinct groundmass. Ordinary light, × 18. Slide 5076.

2. *Porphyritic basalt*, Section C, No. 3. Shows large plagioclase phenocrysts with complex inter-leaved structure. Crossed nicols, × 24. Slide 5079.

3. *Serpentine basalt*, Section A, No. 4. The intersertal-intergranular texture is the most important feature. The small, dark, intersertal, sharply defined wedges are the serpentine-glass mesostasis. Ordinary light, × 25. Slide 5077.

4. *Olivine nephelinite*, from a small gully on the western slopes of Bald Hill. Shows large phenocrysts of olivine, abundant small prisms of groundmass pyroxene, and allotriomorphic plates of nepheline surrounding olivine crystals. Ordinary light, × 34. Slide 5110.

5. *Olivine basalt*, collected from the summit of the Pentland Hills, ½ mile west of Dyke Cliff. Shows idiomorphic laths of labradorite embedded in a dark coloured glass forming 40 to 50 per cent. of the rock. Crossed nicols, × 34.

6. *Limburgite*, Section E, No. 11. Shows a large iddingsitized olivine phenocryst. The brown iddingsite core is surrounded by a border of clear olivine, which, in turn, is rimmed with iddingsite. Ordinary light, × 34. Slide 5104.

GEOLOGICAL SKETCH MAP OF THE KORKUPERRIMUL CREEK AREA.

Based on Quarter Sheets 11 SE and 12 NE, by R. Daintree, C. S. Wilkinson and R. A. F. Murray. (Geol. Surv. of Victoria.). Contours from Military Map of Ballan.